Comparison between J/Ψ and Ψ' Production with Proton and Pion Beams

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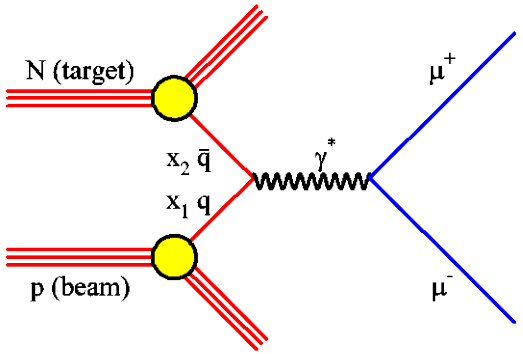
Questions to be addressed

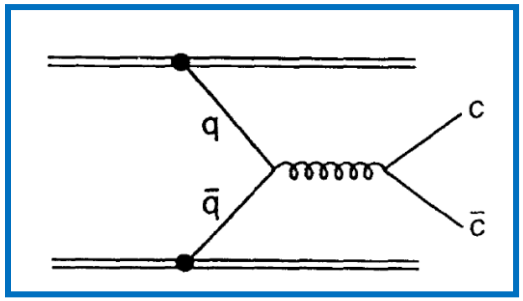
- Do we expect different mechanisms for J/Ψ and Ψ’ production at fixed-target energies?
- What have we learned from J/Ψ and Ψ’ production with proton and pion beams?
- What are the physics opportunities for measuring Ψ’ production at AMBER?

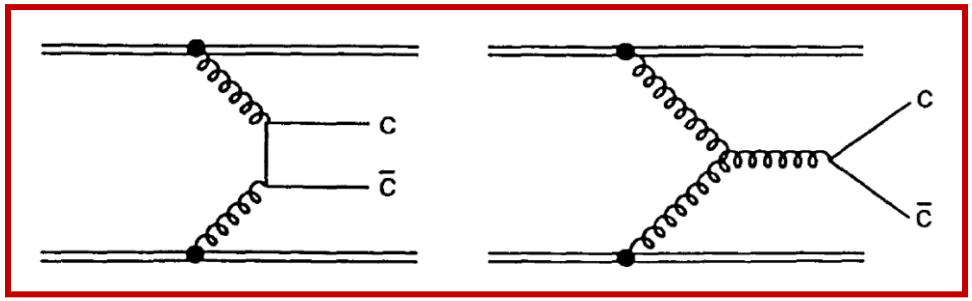
Drell-Yan process versus J/Ψ production

Drell-Yan proceeds via quark-antiquark annihilation in Leading-Order



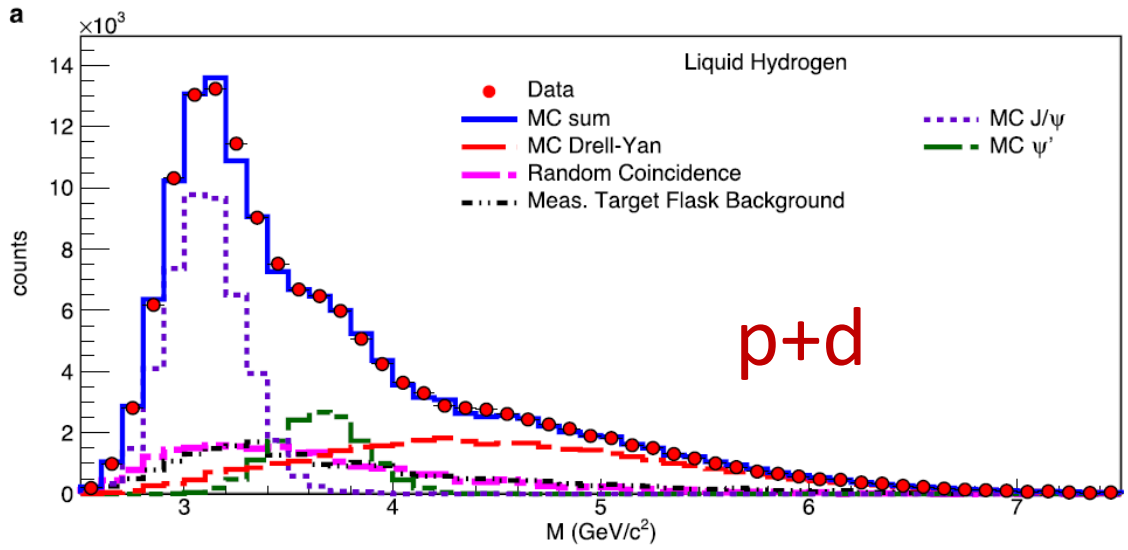
J/Ψ production proceeds via quark-antiquark annihilation and gluon-gluon fusion in LO





J/Ψ production data provide information complementary to the Drell-Yan data

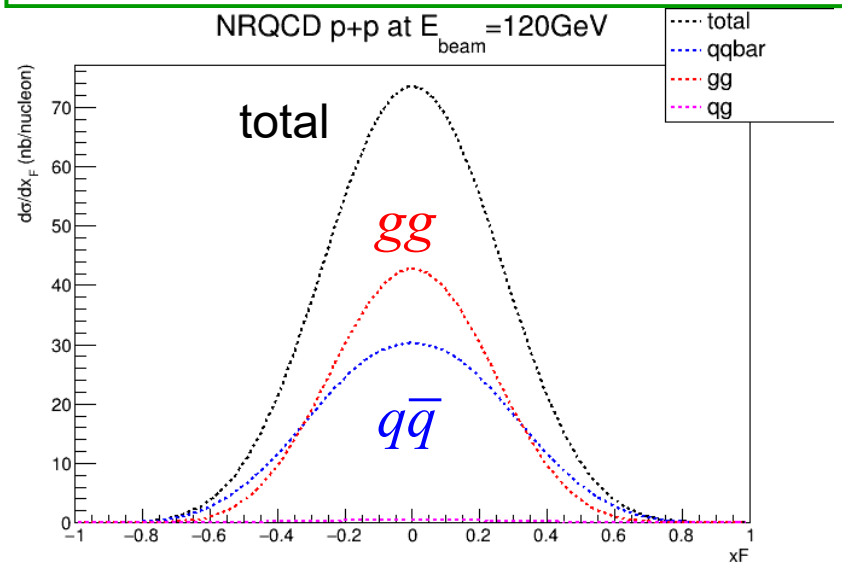
SeaQuest dimuon mass spectrum with 120 GeV proton



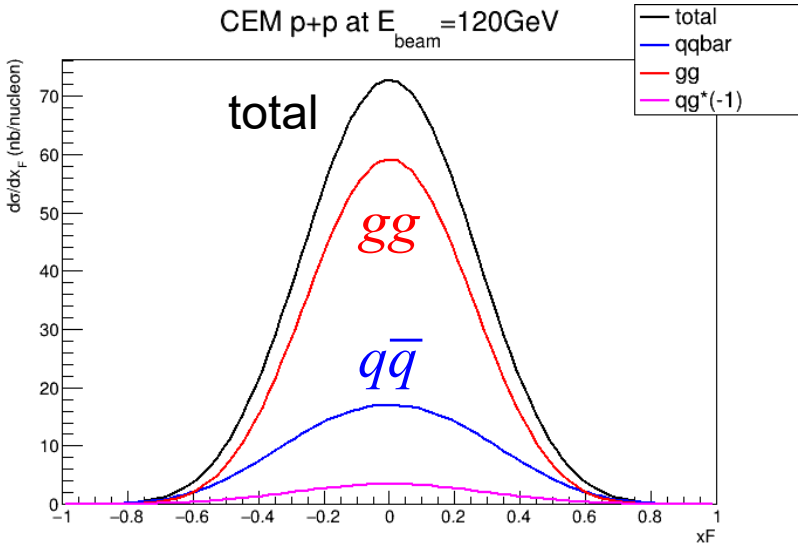
- J/Ψ and Ψ' are clearly observed
- From a fit to the dimuon mass distribution, the J/Ψ and Ψ' events can be extracted
- An analysis has been performed to obtain the (p+d)/2(p+p) cross section ratios for J/Ψ
- Absolute cross sections for J/Ψ production have also been measured

Decomposition of the J/Ψ production cross sections into various processes for two models

NRQCD (Non-relativistic QCD)



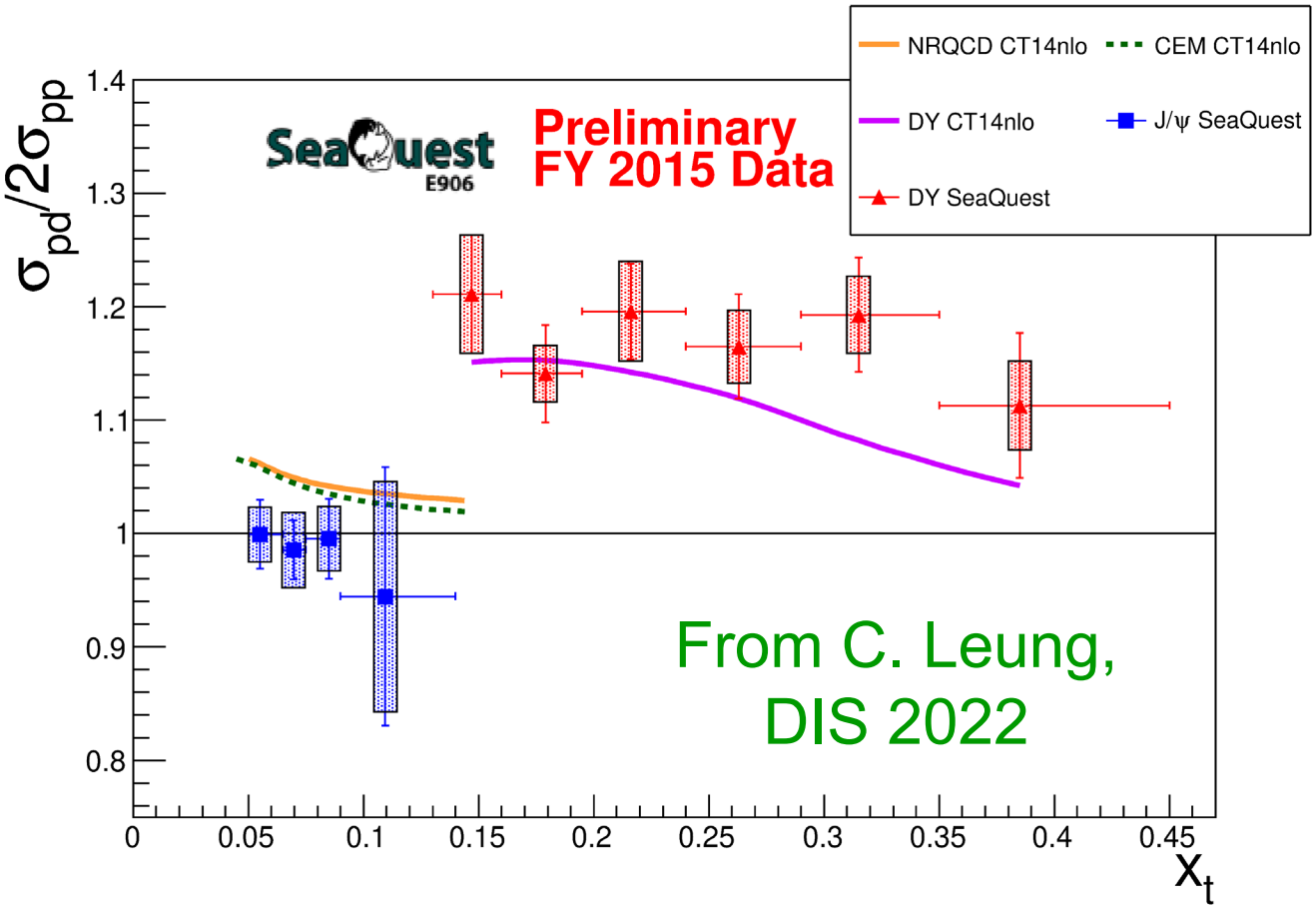
CEM (Color Evaporation Model)



Calculation performed by Wen-Chen Chang

- Both models predict larger gg contributions than $q\bar{q}$
- NRQCD predicts relatively larger $q\bar{q}$ contribution than CEM
- NRQCD predicts absolute cross section, but CEM does not
- NRQCD contains LDMEs (Long-distance-matrix-elements) for the hadronization probabilities for various $c\bar{c}$ configurations

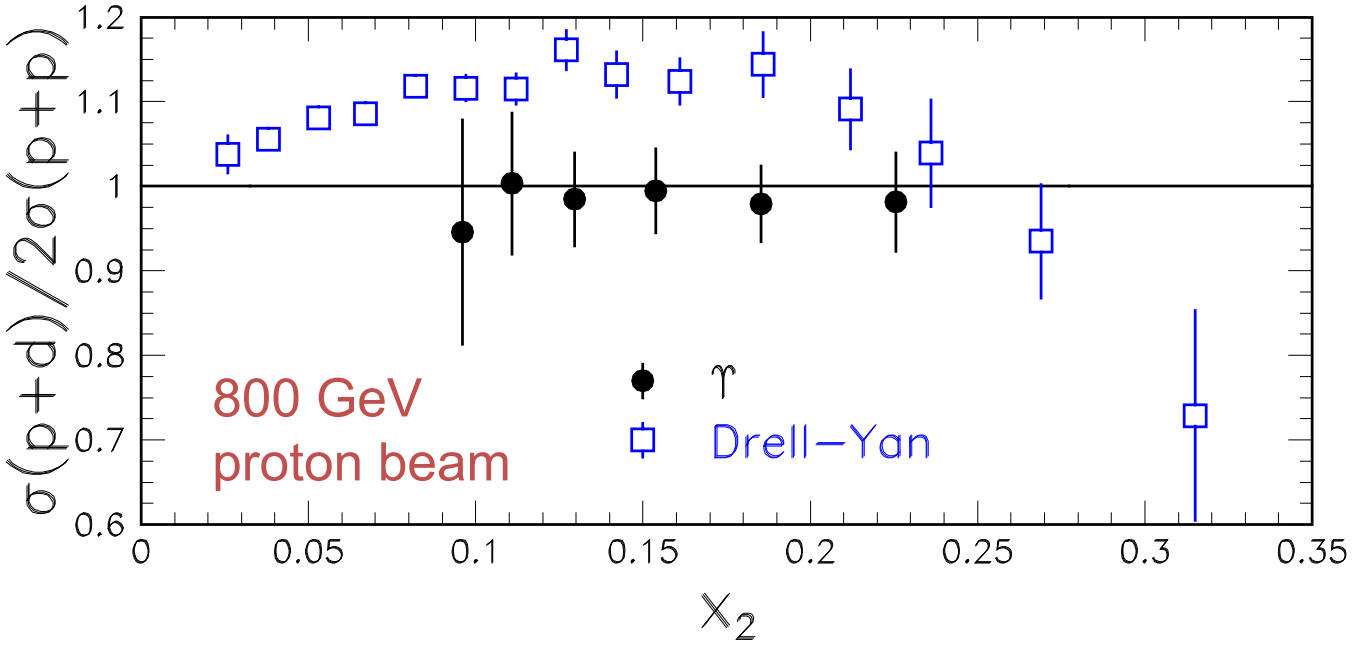
Comparison of $\sigma_{pd}/2\sigma_{pp}$ for Drell-Yan versus J/Ψ



- J/Ψ production is dominated by gluon-gluon fusion process
- J/Ψ ratio should be 1, if gluon content of proton is the same as neutron
- The data show distinct difference for Drell-Yan and J/Ψ cross section ratios

Gluon distributions in proton versus neutron?

$$\text{E866 data}: \sigma(p+d \to \Upsilon X)/2\sigma(p+p \to \Upsilon X)$$



Lingyan Zhu et al., PRL, 100 (2008) 062301 (arXiv: 0710.2344)

$$Drell-Yan: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+\bar{d}(x)/\bar{u}(x)]/2$$

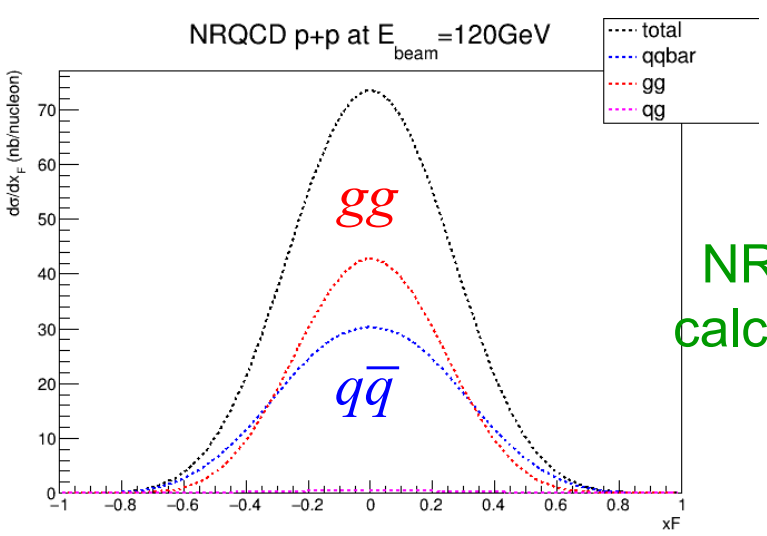
$$J/\Psi, \Upsilon: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+g_n(x)/g_p(x)]/2$$

Gluon distributions in proton and neutron are very similar

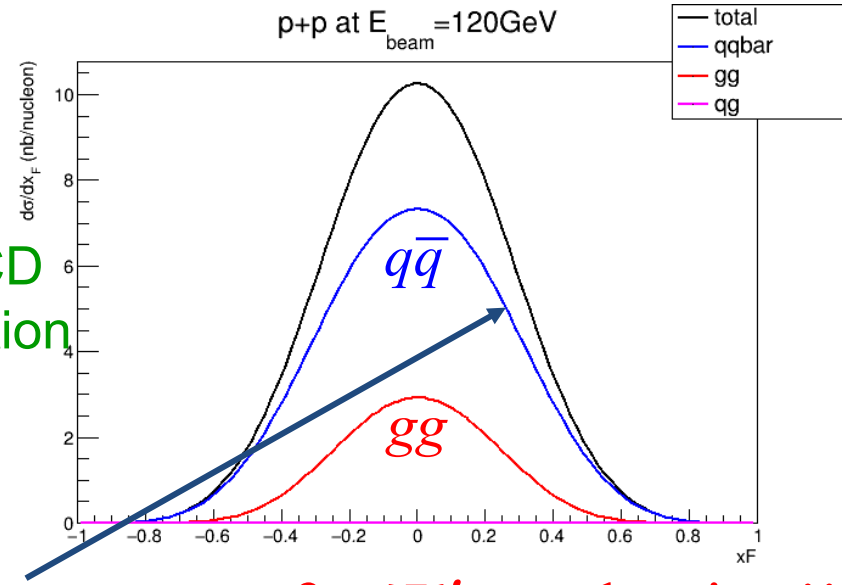
New data on $\sigma(p+d \to J/\Psi)/2\sigma(p+p \to J/\Psi)$ expected for E906

Comparison between J/Ψ and Ψ'

J/Ψ p+p at 120 GeV Ψ'



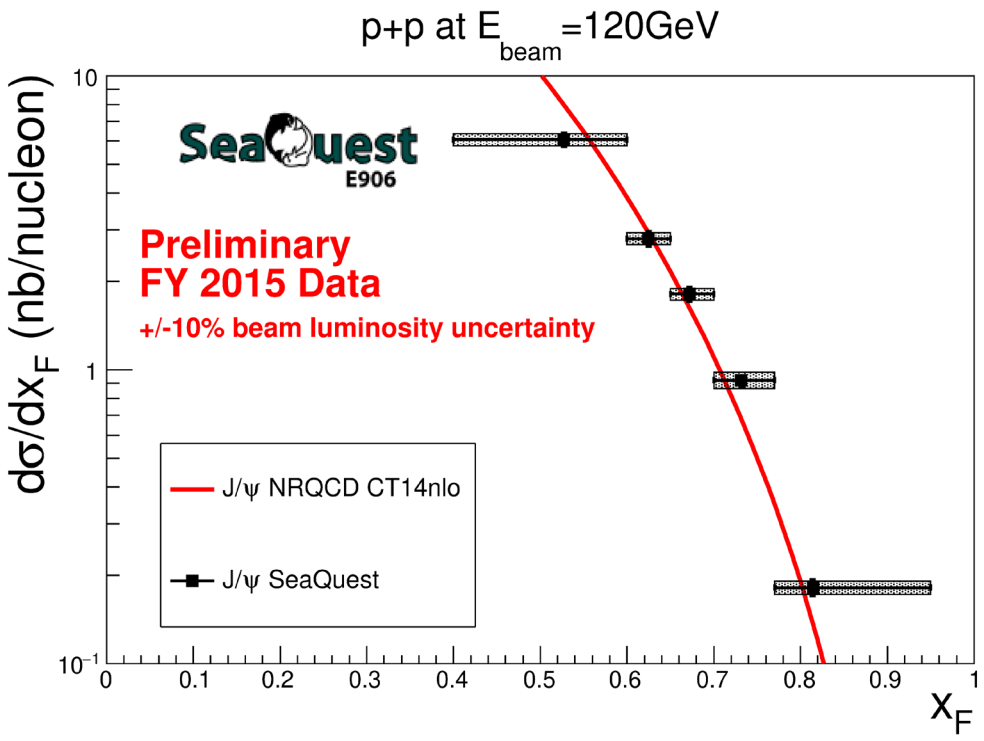
NRQCD calculation



$q\bar{q}$ annihilation is the dominant process for Ψ′ production!!!

- This suggests the possibility of using the J/Ψ and Ψ' data to separate the gg from the $q\bar{q}$ contributions
- This also suggests the possibility to separate the antiquark and gluon contents using the J/Ψ and Ψ' data (without using the Drell-Yan data!)
- Are there other evidences for the differences between the J/Ψ and Ψ' production mechanisms (namely, J/Ψ has more gg, and Ψ' has more $q\bar{q}$ contributions)?

J/Ψ cross section for p+p at 120 GeV from SeaQuest (Preliminary)

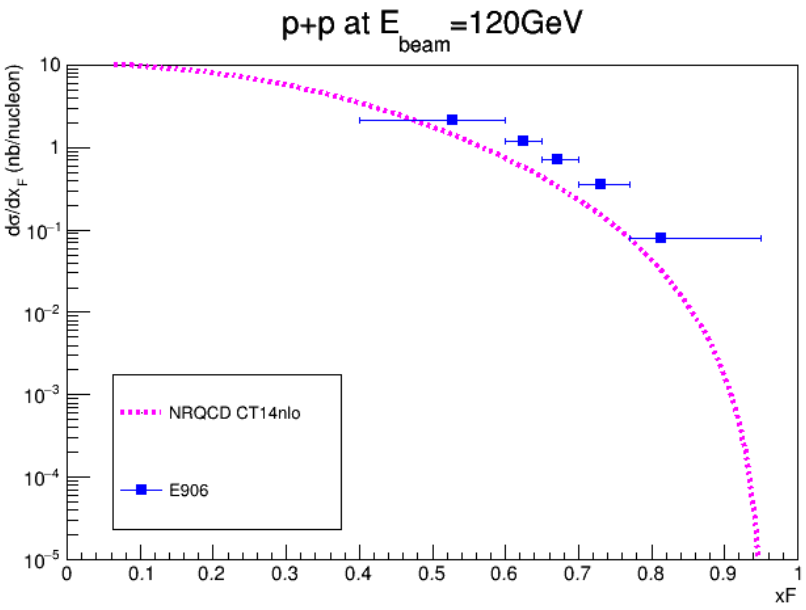


From C. Leung, DIS 2022

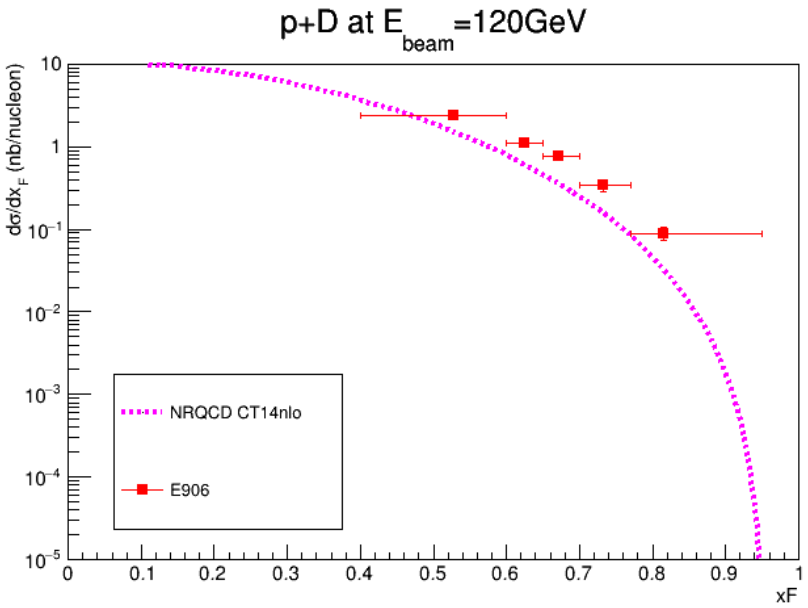
- The solid red line is prediction from NRQCD with CT14nlo PDF
- Very similar shape is obtained with CEM model
- The absolute cross section from NRQCD is in reasonable agreement with the data

Ψ’ cross section for p+p and p+d at 120 GeV from SeaQuest (Preliminary)

p + p

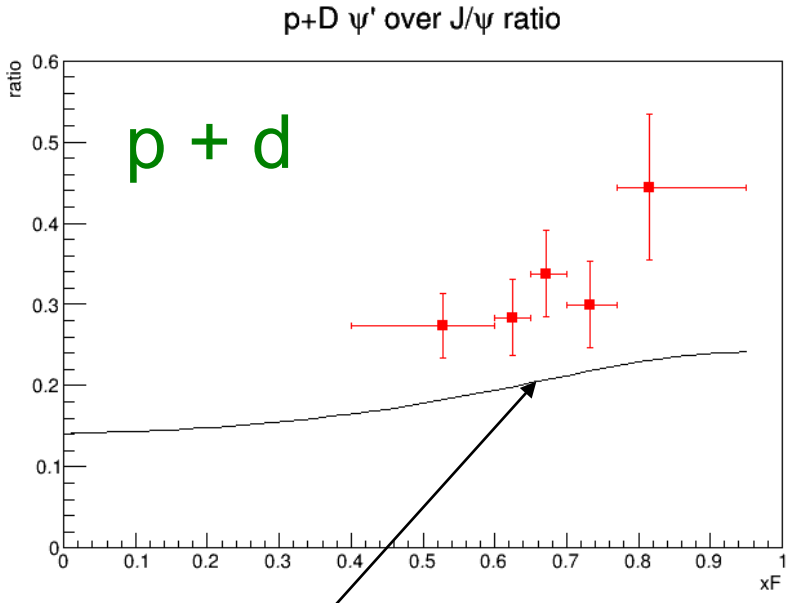


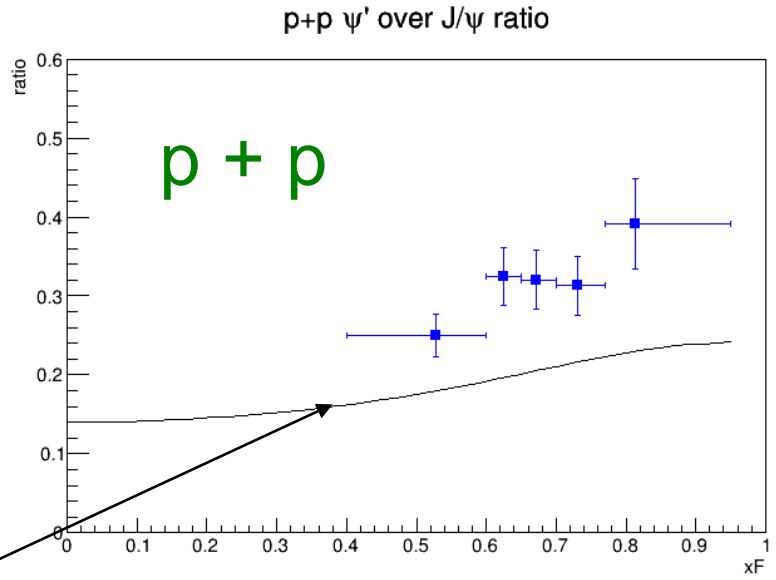
p + d



Shape is in agreement with NRQCD, but the magnitude appears to be off by a constant factor

Ψ'/(J/Ψ) ratio in SeaQuest (VERY PRELIMINARY)





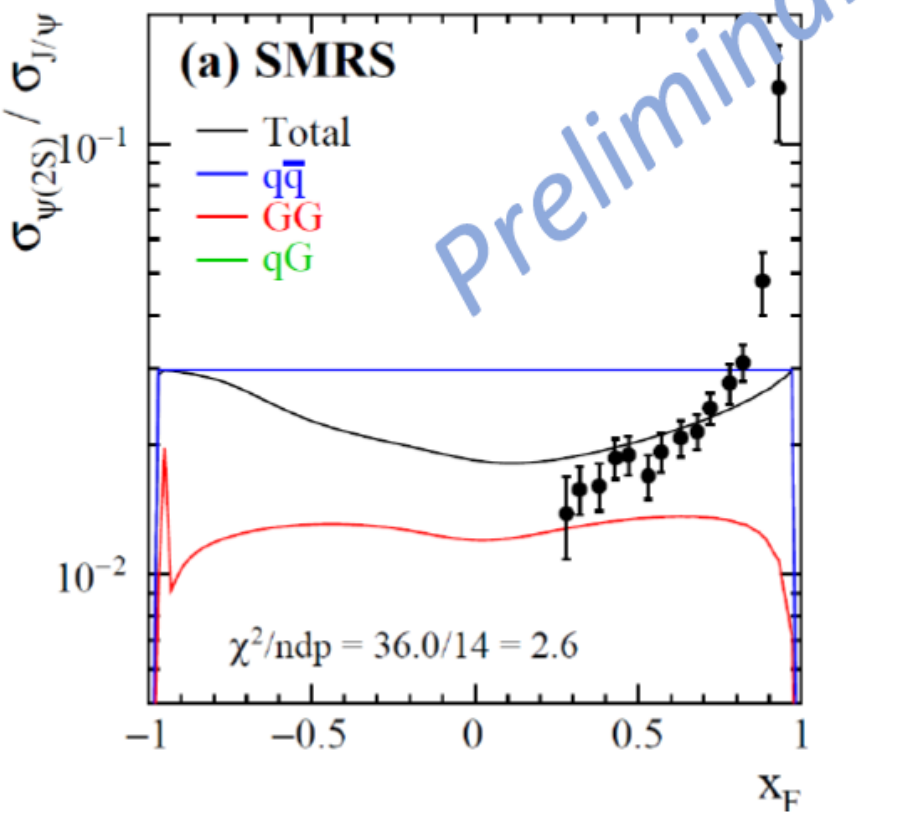
NRQCD calculations from Wen-Chen Chang

From C. Leung's analysis

- The positive slope in both the data and the NRQCD calculation shows Ψ' has a broader x_F distribution than J/Ψ
- The data are different from CEM model calculation which predicts a flat Ψ'/(J/Ψ) ratio

Ψ'/(J/Ψ) ratio with pion beam

[$\pi^- + W \rightarrow Jpsi/psi' + X$ at 253 GeV, Phys. Rev. D 53, 4723 (1996)]

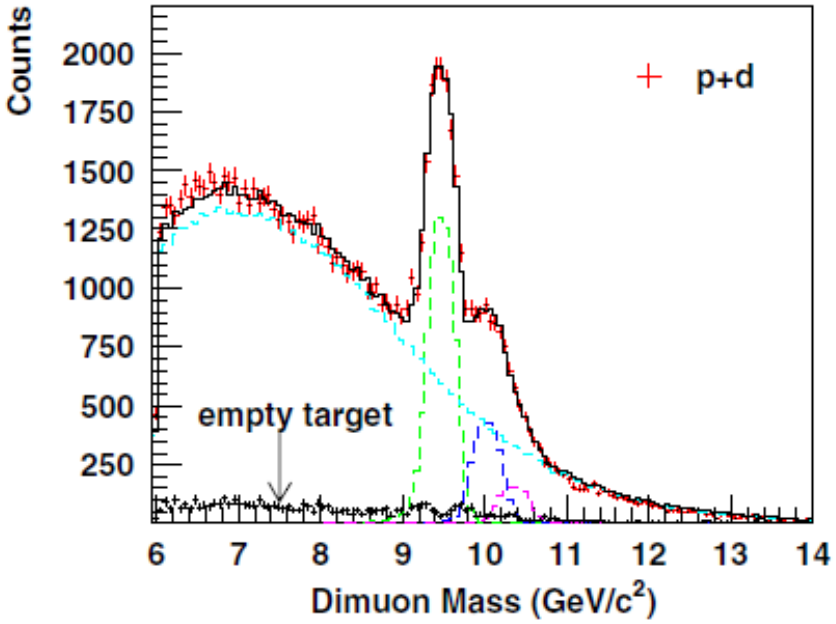


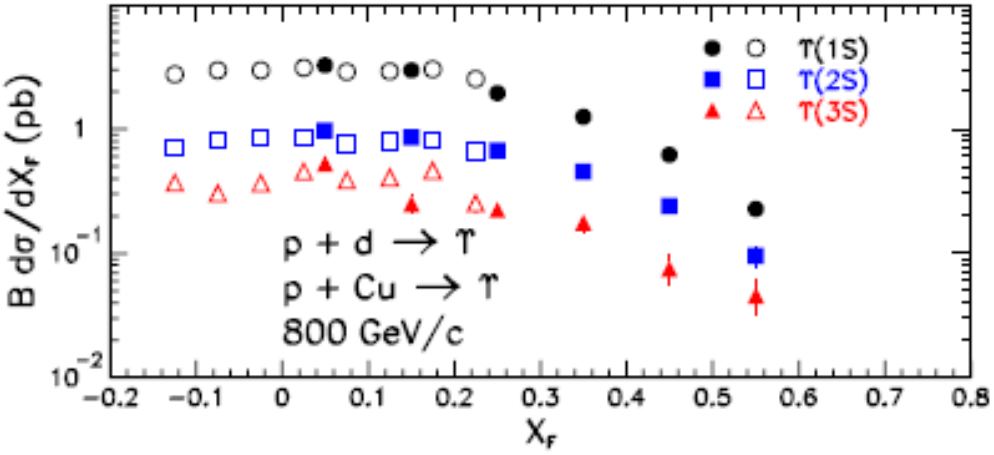
From Wen-Chen Chang's talk

How about Υ'/ Υ ratios ?

PRL 100, 062301 (2008) PHYSICAL REVIEW LETTERS week ending 15 FEBRUARY 2008

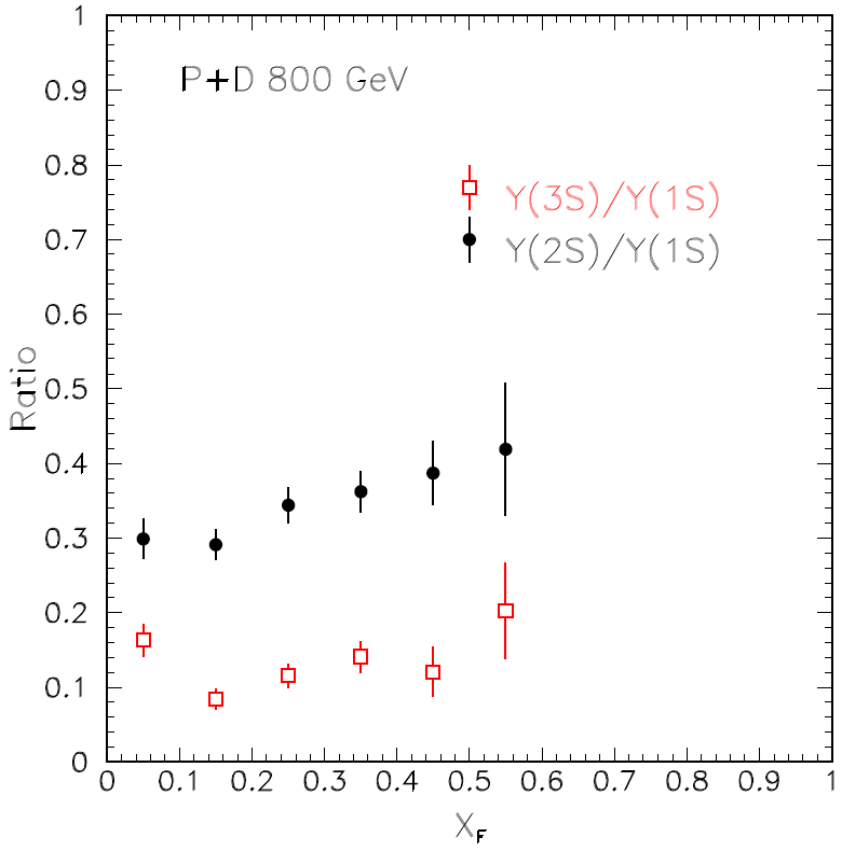
Measurement of Υ Production for $p + p$ and $p + d$ Interactions at 800 GeV/c





One can form the Υ(2S)/ Υ(1S) and Υ(3S)/ Υ(1S) ratios from the above E866 data

How about Υ'/ Υ ratios ?



- The E866 data on Υ – production also suggests a broader x_F distribution for $\Upsilon(2S+3S)$ than for $\Upsilon(1S)$
- This suggests a larger $q\bar{q}$ contribution for $\Upsilon(2S+3S)$ than for $\Upsilon(1S)$
- Are there other evidences?

Polarization of J/Ψ, Ψ′ and ϒs

- Decay angular distribution in the quarkonium rest frame (p_T=0)

$$\frac{d\sigma}{d\Omega} \sim 1 + \lambda \cos^2\theta$$

  * Transverse : σ_T ; helicity: ± 1; $\lambda = 1$
  * Longitudinal : σ_L ; helicity: 0; $\lambda = -1$
  * Unpolarized : $\sigma_T = 2\sigma_L$; helicity: $0, \pm 1$; $\lambda = 0$

- $\lambda = \dfrac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L} = (1 - 2\sigma_L / \sigma_T) / (1 + 2\sigma_L / \sigma_T)$

- σ_L / σ_T depends on the color - spin states of the $Q\bar{Q}$ pair :

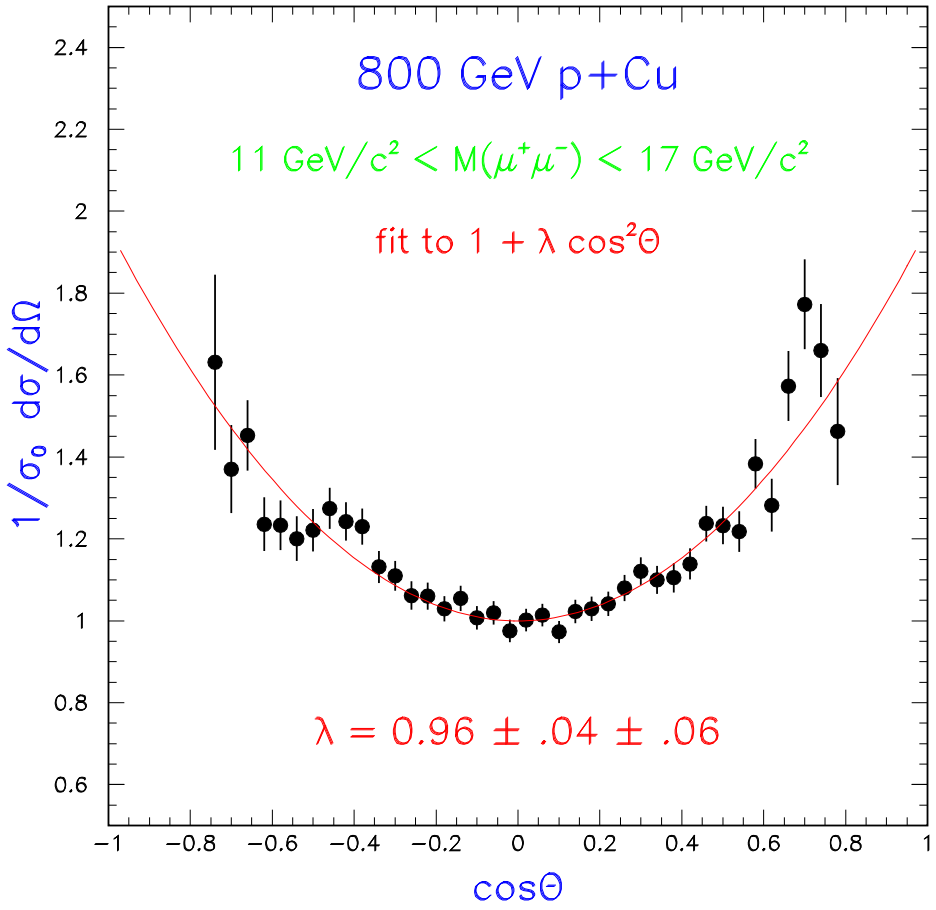
State:	$^3S_1^{(1)}$	$^1S_0^{(8)}$	$^3P_J^{(8)}$	$^3S_1^{(8)}$
σ_L / σ_T :	1 / 3.4	1 / 2	1 / 6	0 / 1

- Polarization of $Q\bar{Q}$ is sensitive to the production mechanism

Drell-Yan angular distribution

Decay Angular Distribution of "naïve" Drell-Yan:

$$\frac{d\sigma}{d\Omega} = \sigma_0(1+\cos^2\theta)$$



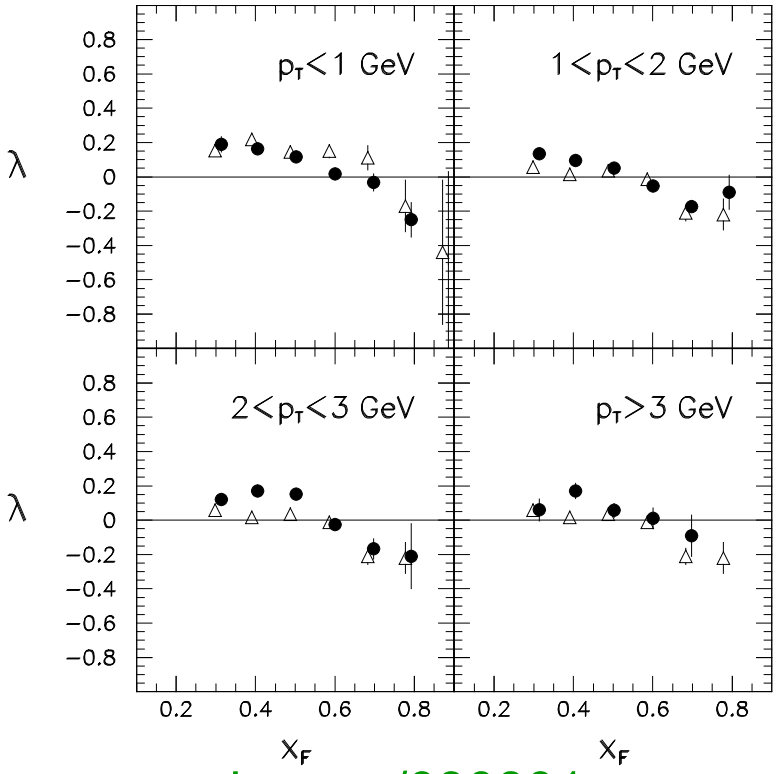
Data from Fermilab E772

Polarization of J/Ψ in p + Cu Collision

$d\sigma/d\Omega \sim 1 + \lambda \cos^2\theta$

(λ=1: transversely polarized, λ = -1: longitudinally polarized
λ = 0, unpolarized)

E866 data



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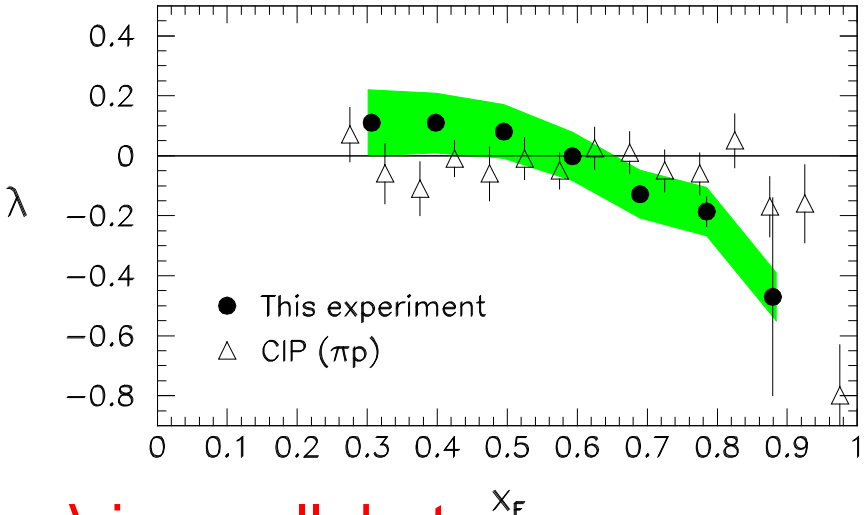
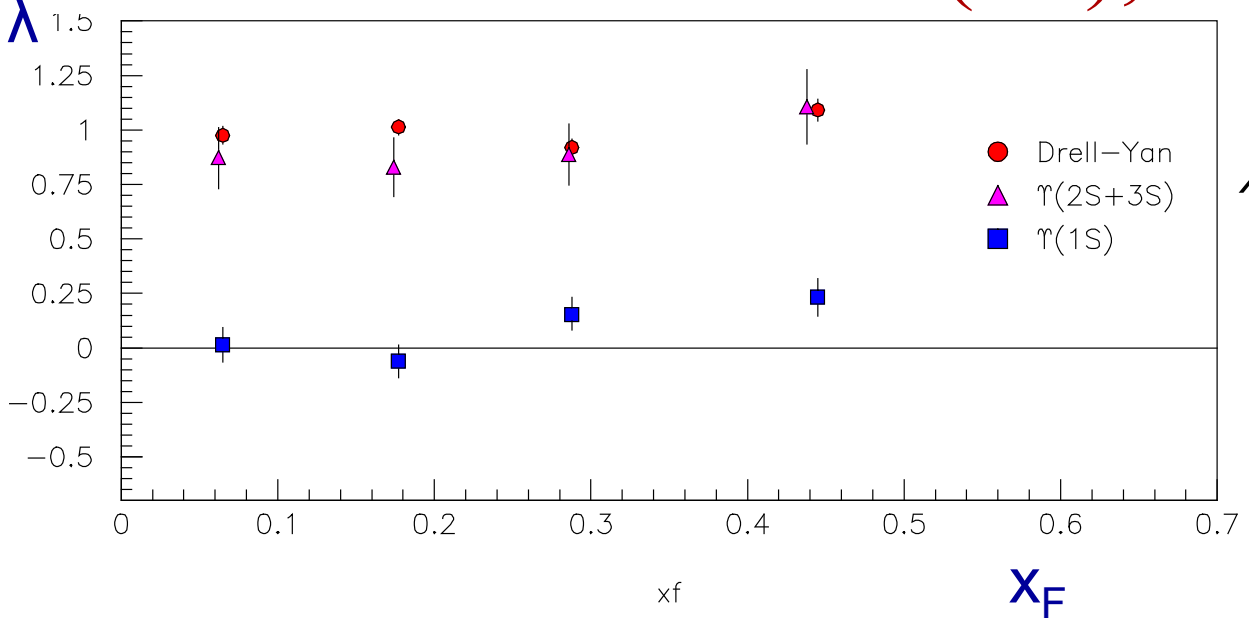


- λ is small, but nonzero
- λ becomes negative at large x_F
- No strong p_T dependence for λ

Polarization of $\Upsilon(1S)$, $\Upsilon(2S+3S)$



λ for D-Y, $\Upsilon(1S)$, $\Upsilon(2S+3S)$

$p + Cu \rightarrow \mu^+\mu^-$

at 800 GeV

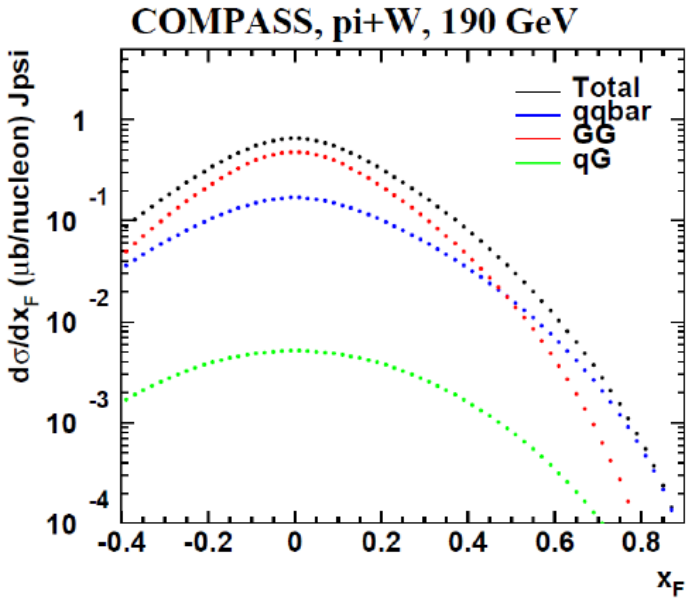
PRL 86, 2529 (2001)

- D-Y is transversely polarized
- Y(1S) is slightly polarized (like J/Ψ)
- Y(2S+3S) is transversely polarized!
- Preliminary result shows ψ' is also transversely polarized!

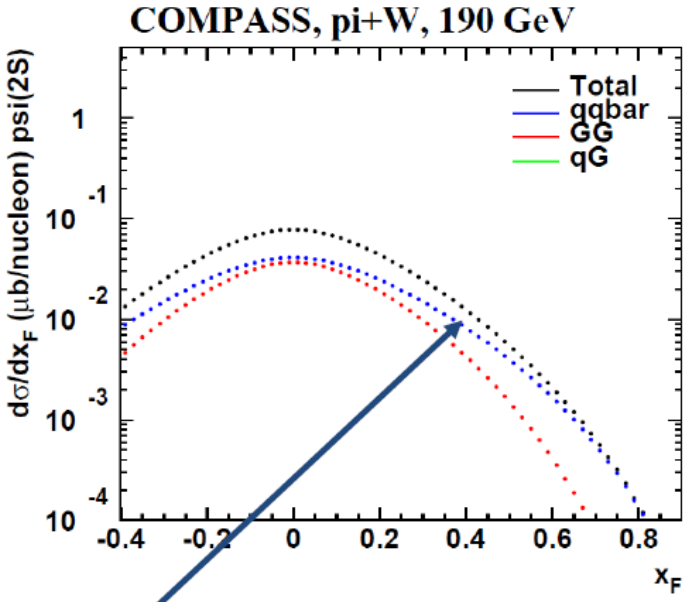
It would be very interesting to measure J/Ψ and Ψ' polarization in SeaQuest and COMPASS/AMBER (expect difference between J/Ψ and Ψ')

Comparison between J/Ψ and Ψ' for π+W at COMPASS (calculation by Wen-Chen Chang)

J/Ψ



Ψ'

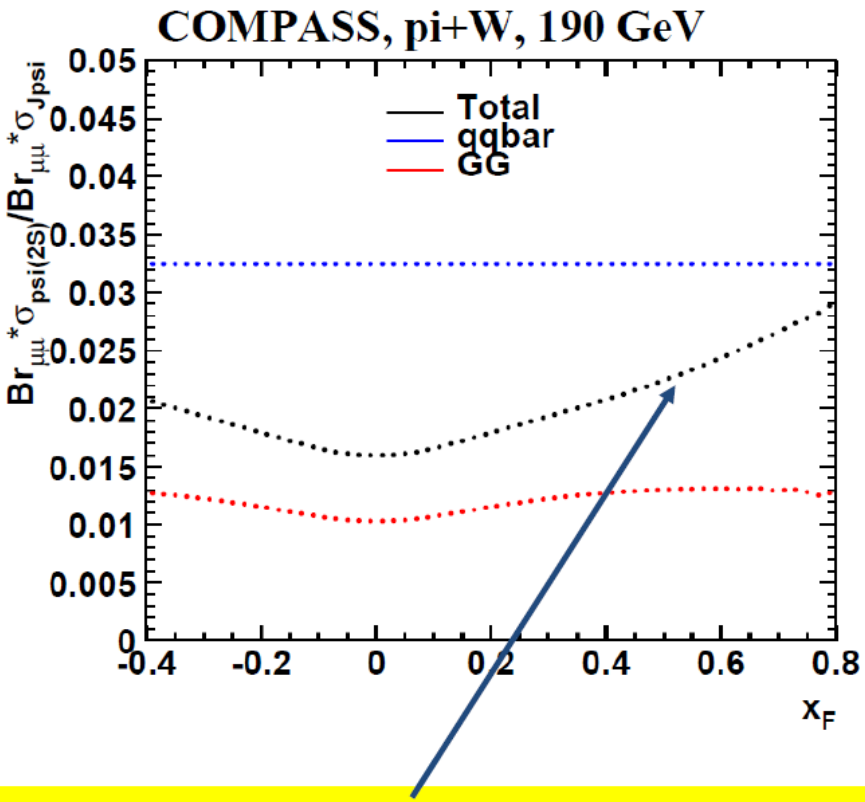


$q\bar{q}$ annihilation is the more dominant process for Ψ′ production!!!

- This suggests the possibility of using the J/Ψ and Ψ' data to separate the gg from the $q\bar{q}$ contributions (gluon Sivers versus quark Sivers in TSSA)
- This also suggests the possibility of different polarization for the COMPASS J/Ψ and Ψ' data
- The cross section ratio of Ψ' / (J/Ψ) is expected to have a postive slope for $x_F > 0$

Comparison between J/Ψ and Ψ' for π+W at COMPASS (calculation by Wen-Chen Chang)

Ψ' / (J/Ψ)



- The cross section ratio of Ψ' / (J/Ψ) is expected to have a postive slope for $x_F > 0$

Possible implications for COMPASS/AMBER

- J/Ψ and Ψ′ provide complementary information, since the $q\bar{q}$ and gg contributions for them are different
- Analysis of J/Ψ and Ψ′ production cross sections and polarization for the COMPASS data on NH_3 and W targets would be interesting
- Obtain the Ψ′ / (J/Ψ) cross section ratio versus x_F. Check if the ratio has a positive slope
- Check if Ψ′ has larger polarization than J/Ψ ?
- Improved mass resolution in AMBER would enable improved measurement of Ψ′
- Ψ′ production with kaon beam in AMBER would be new measurements